International conference on Critical Point and Onset of Deconfinement
15 March 2021

Flow fluctuations in heavy-ion collisions measured with ALICE

Zuzana Moravcová
on behalf of the ALICE Collaboration

zuzana.moravcova@cern.ch

Niels Bohr Institute, University of Copenhagen

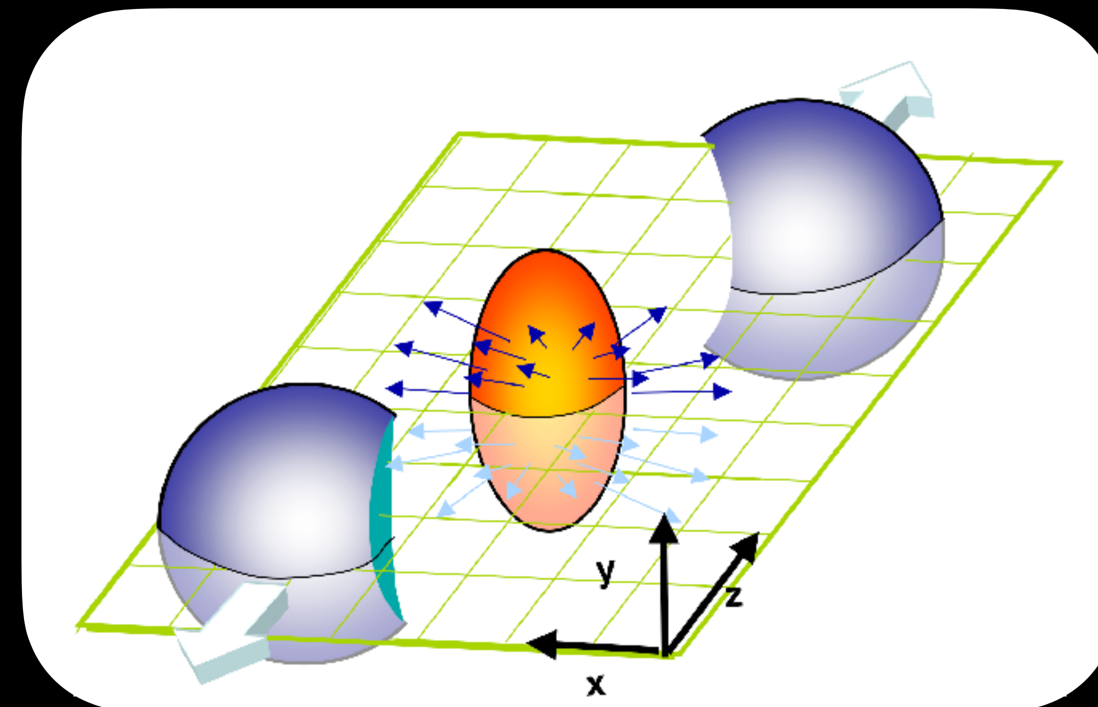
THE VELUX FOUNDATIONS
VILLUM FONDEN VELUX FONDEN

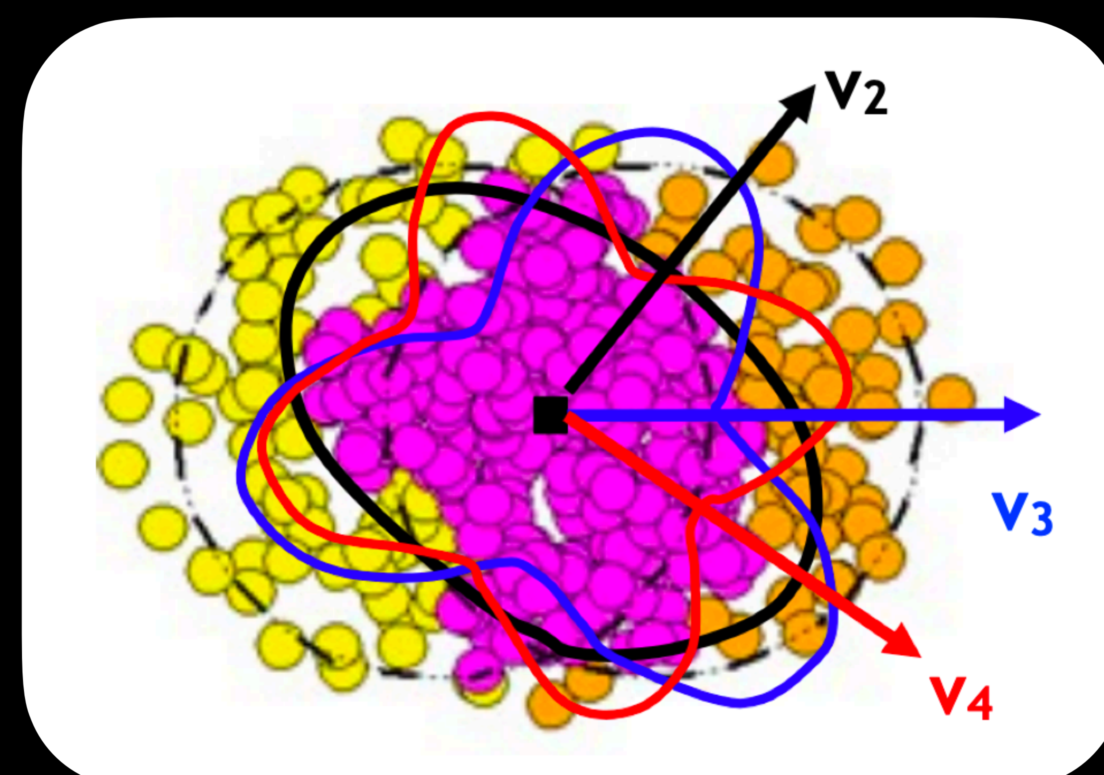
Anisotropic flow

- Partial overlap ⇨ Spatial anisotropy ⇨
  ⇨ Different pressure gradients ⇨
  ⇨ Particles "flow"
- Fourier series decomposition of azimuthal distribution of emitted particles:

$$\frac{\mathrm{d}N}{\mathrm{d}\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos n(\varphi - \Psi_n)$$

- Ψ_n — flow symmetry plane (defined by xz)
- v_n — flow coefficients
  - Nowadays typically calculated using m-particle correlations, $v_n\{m\}$
- Together they make flow vector $\overrightarrow{V}_n = v_n e^{in\Psi_n}$



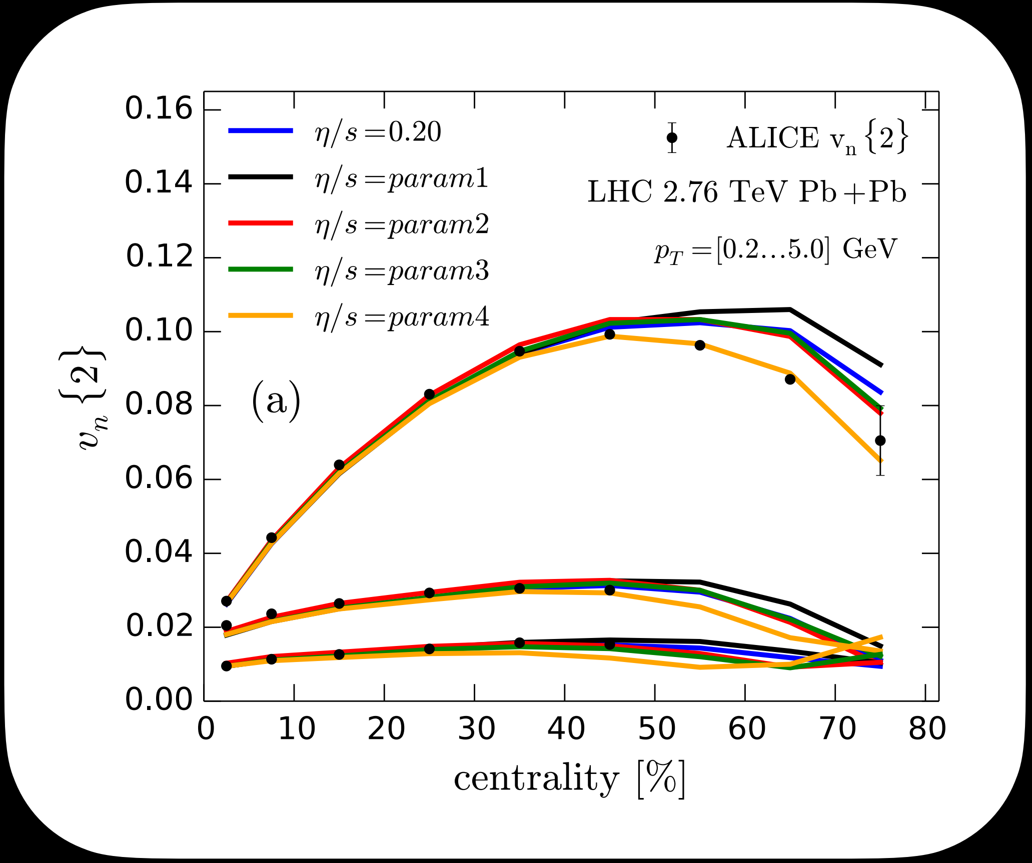


Measuring flow vector

- Two ways how to measure flow vector
  - Multi-particle correlations
  - Event-shape engineering
- What information can measuring of flow vector provide?
  - Initial-state conditions (initial geometry)
  - QGP properties, e.g. transport coefficients (shear viscosity η/s, bulk viscosity ξ/s) as a function of temperature

⇨

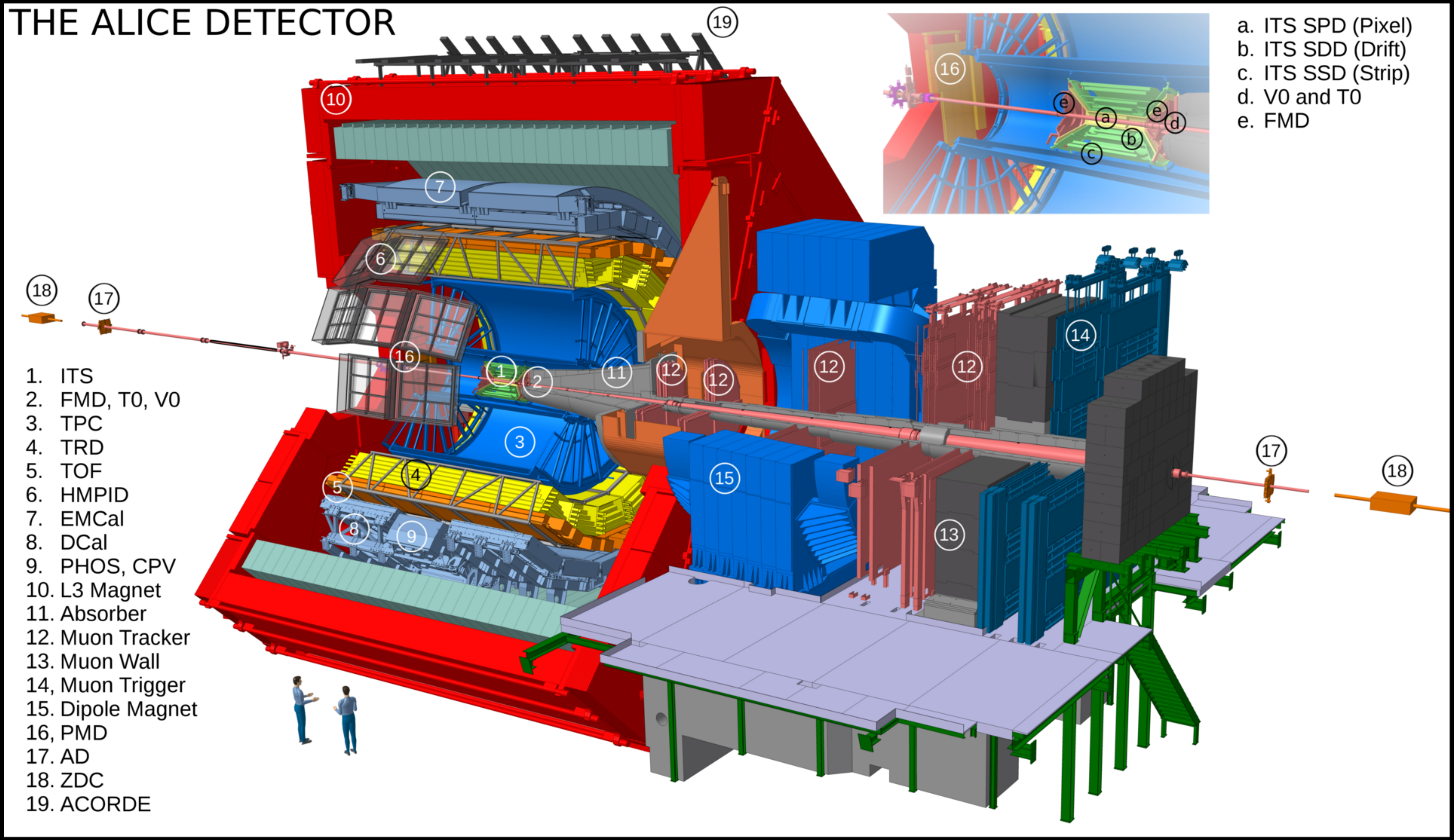
- Event-by-event v_2 distribution
- Event-by-event fluctuations of the flow vector
- Correlations between different flow vectors



Phys. Rev. C 93, 024907 (2016)

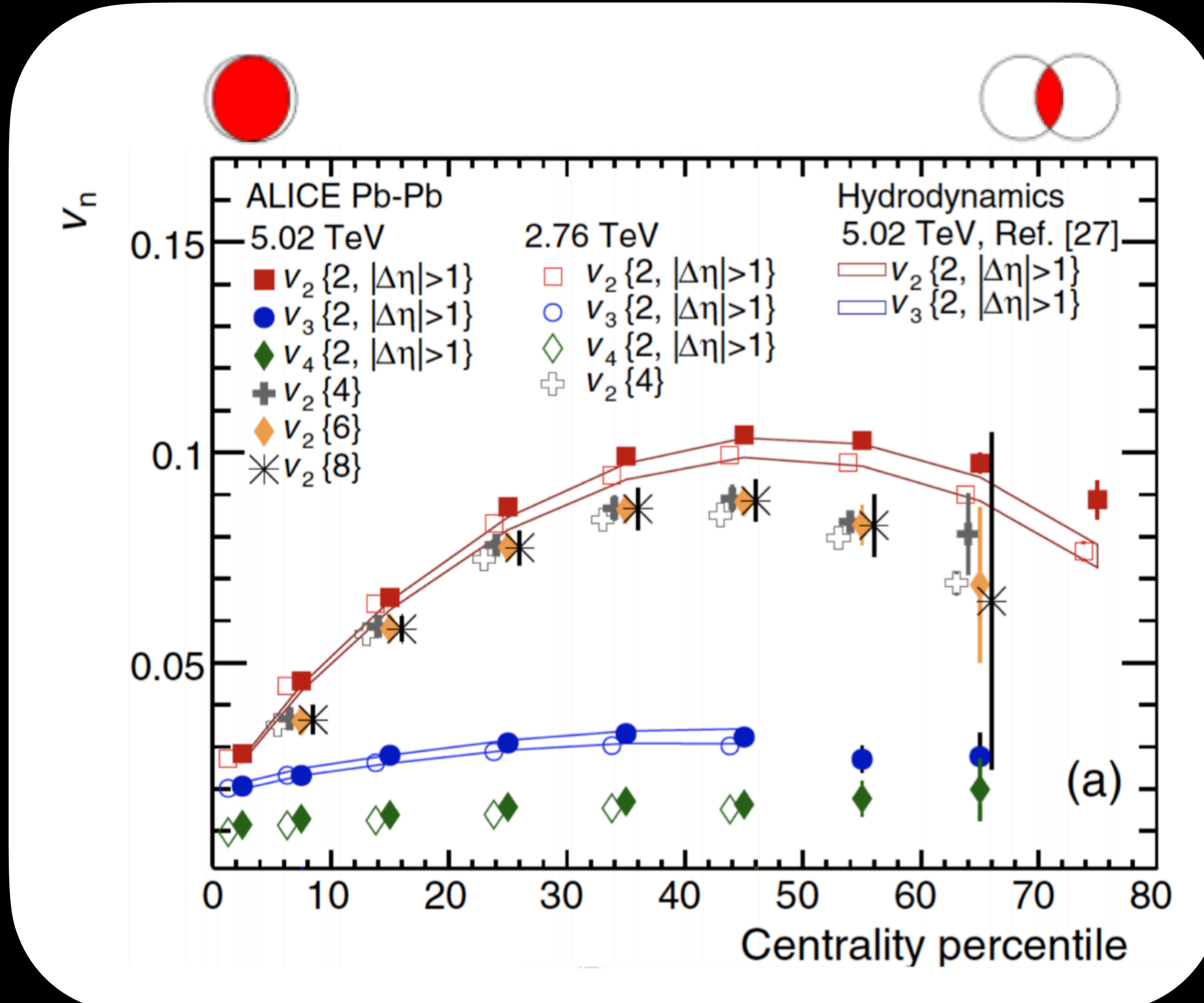
ALICE detector

- General-purpose heavy-ion experiment at the Large Hadron Collider
- Pb-Pb collisions at 5.02 TeV (taken in 2015 and 2018)

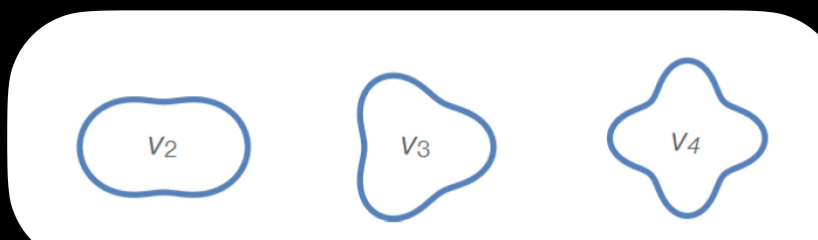


Flow of charged hadrons

- Ordering $v_2 > v_3 > v_4$
- Elliptic flow (v_2) is dominant in non-central heavy-ion collision where the overlap of colliding nuclei has an almond-like shape
- v_3 originates from fluctuations
- v_4 originates from the initial geometry and fluctuations
- Hydrodynamic description in a very good agreement with data

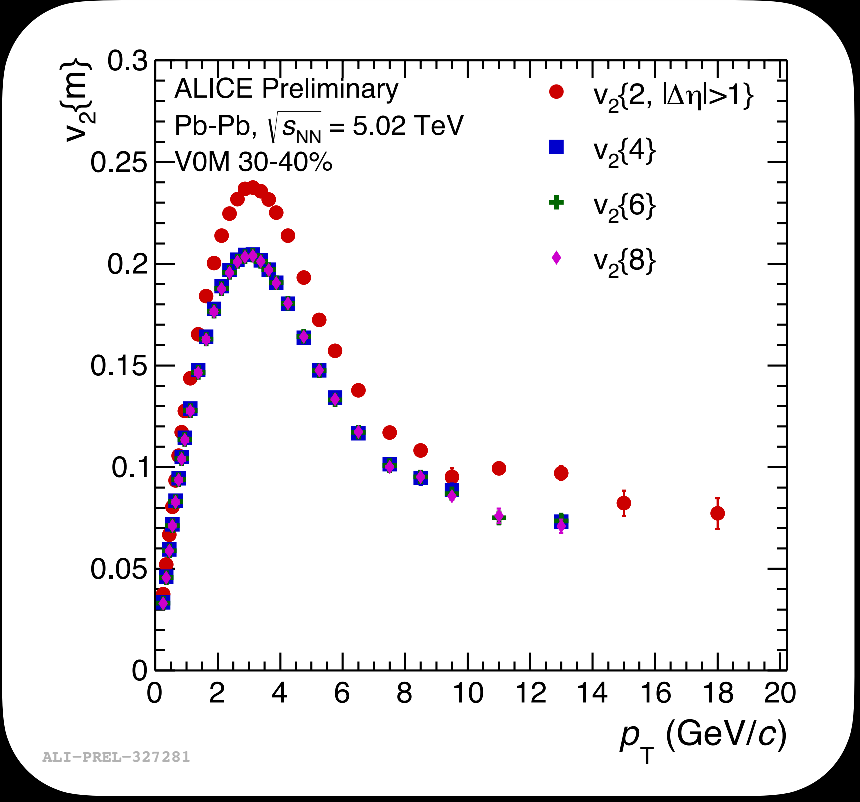


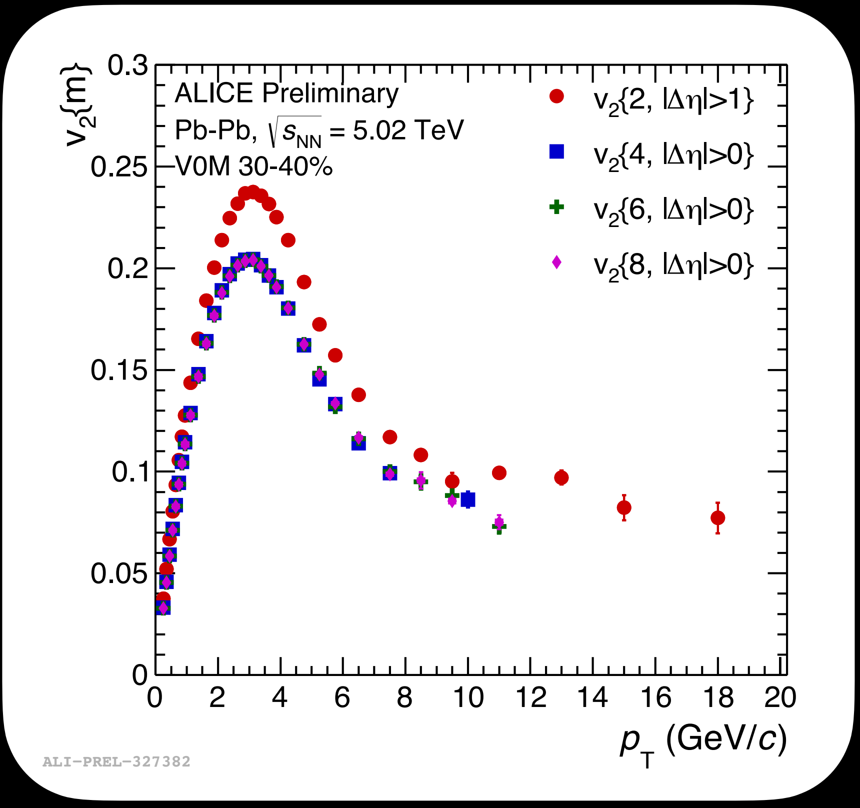
Phys. Rev. Lett. 116, 132302 (2016)



Multi-particle cumulants

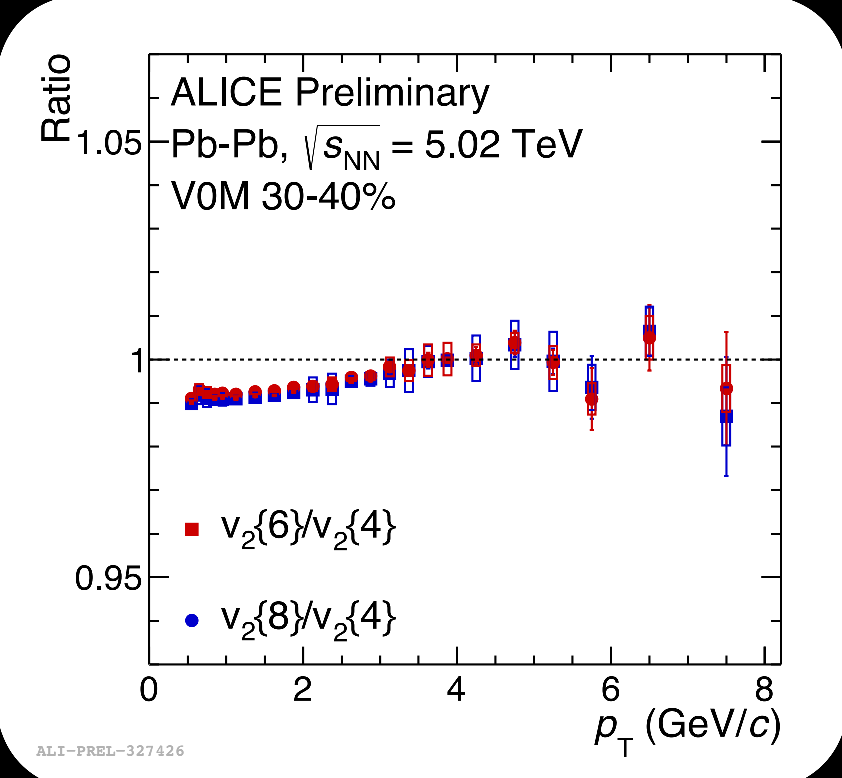
- Initial geometry fluctuations result in fluctuations in the final state
  - $\langle v_2^k \rangle \neq \langle v_2 \rangle^k$
  - Probability density function of v_n can be studied using multi-particle cumulants (= genuine multi-particle correlations)
- Different orders can provide different information
  - $v_2\{2, |\Delta\eta| > 1\} > v_2\{4,6,8\}$, flow fluctuations
  - $v_2\{4,6,8\} \approx v_2\{4,6,8, |\Delta\eta| > 0\}$, less sensitive to non-flow
  - Non-flow = correlations not associated with the common symmetry plane, originating e.g. from jets or resonance decays

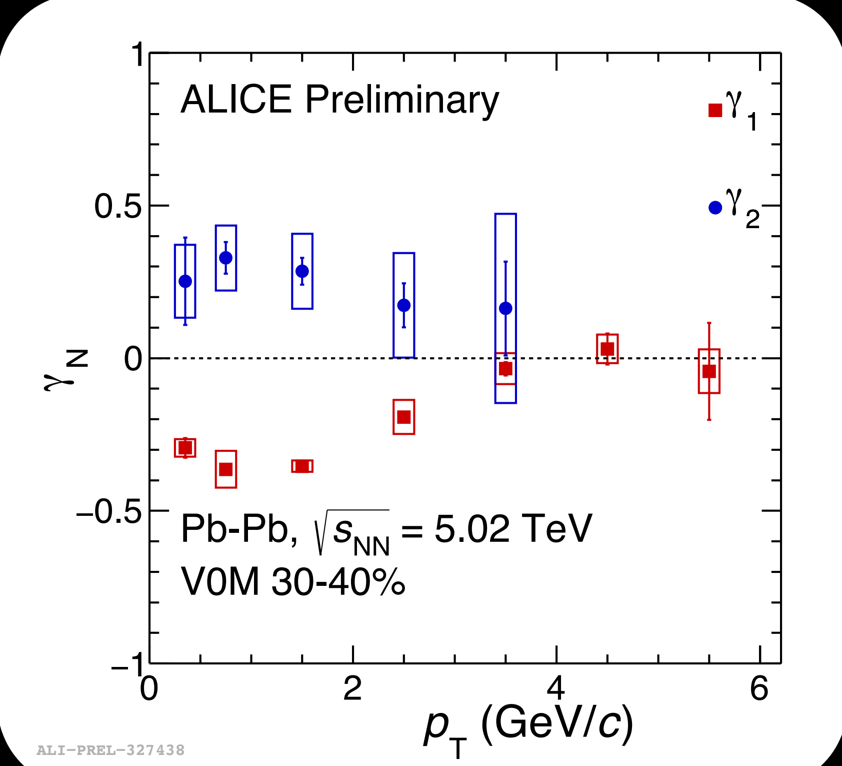




Probability density function of v_2

- Bessel-Gaussian *p.d.f.* if $v_2\{4\} = v_2\{6\} = v_2\{8\}$
  - Agrees above approx. 3.5 GeV/*c*
- Possible to calculate higher-order moments of the *p.d.f.*
  - Skewness γ_1 — negative at low p_T
  - Kurtosis γ_2 — positive at low p_T
  - Consistent with Bessel-Gaussian *p.d.f.* above approx. 3.5 GeV/*c*
- Probability density function of v_2 has non-trivial transverse momentum dependence



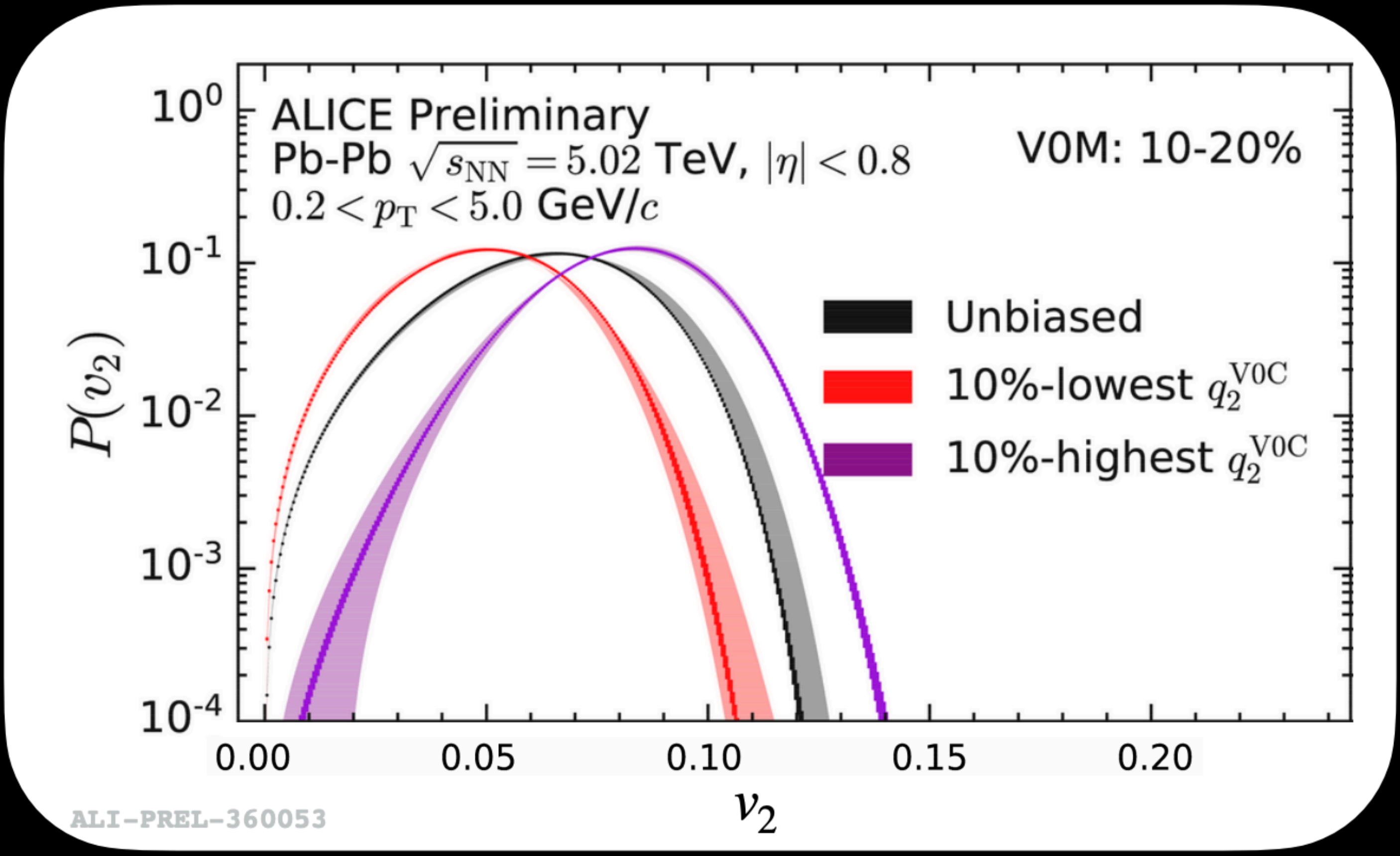


P.d.f. with event-shape engineering

- Event-shape engineering (ESE) [1] allows a selection of initial geometry, e.g. specific eccentricities (larger/smaller)
- q_2 selection by constructing reduced flow vector, $q_n = \frac{|Q_n|}{\sqrt{M}}$,

$$|Q_n| = \sqrt{Q_{n,x}^2 + Q_{n,y}^2}$$

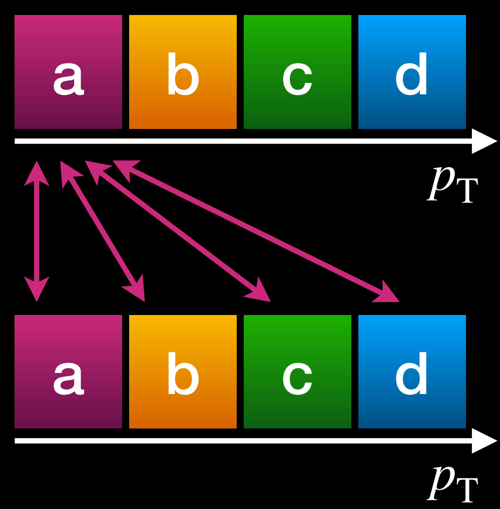
- Selecting q_2 ⇨ selecting eccentricity ⇨ different v_2 distribution (e.g. more skewed probability density function)

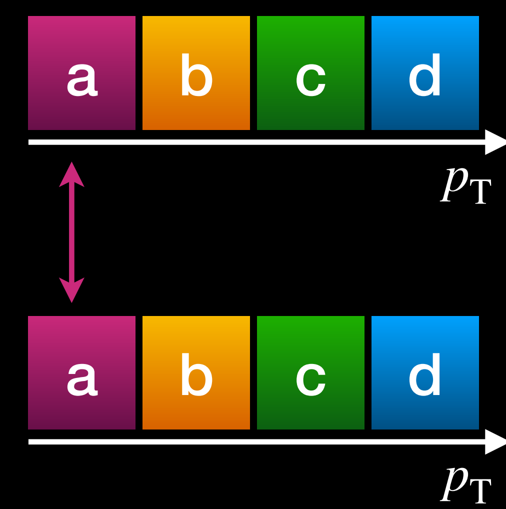


[1] Schukraft, Timmins, Voloshin PLB 719, 4–5, 394-398 (2013)

Flow vector fluctuations

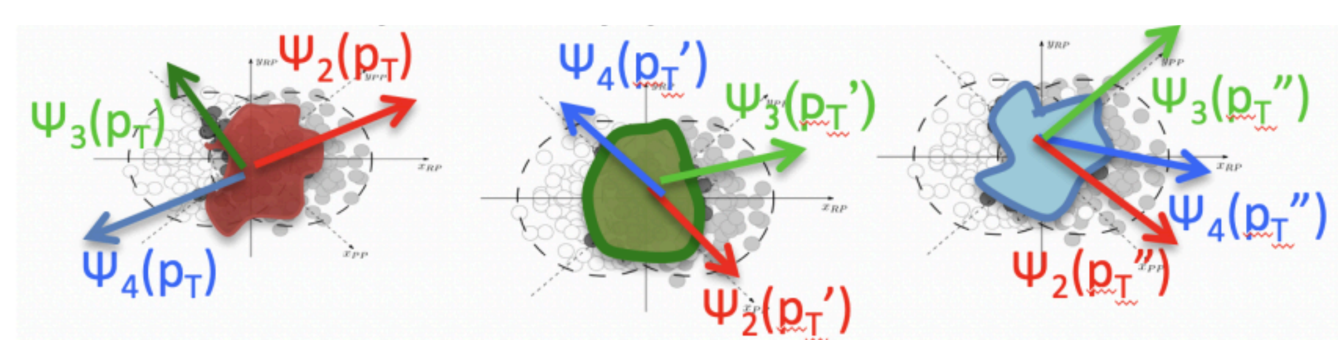
$$\langle v_n(p_T^a) \cdot v_n(p_T^b) \rangle \neq \langle v_n(p_T^a) \rangle \cdot \langle v_n(p_T^b) \rangle$$





Angle — final symmetry plane

Hydrodynamic models show its p_T dependence



How to disentangle contributions to fluctuations from flow magnitude and flow angle?

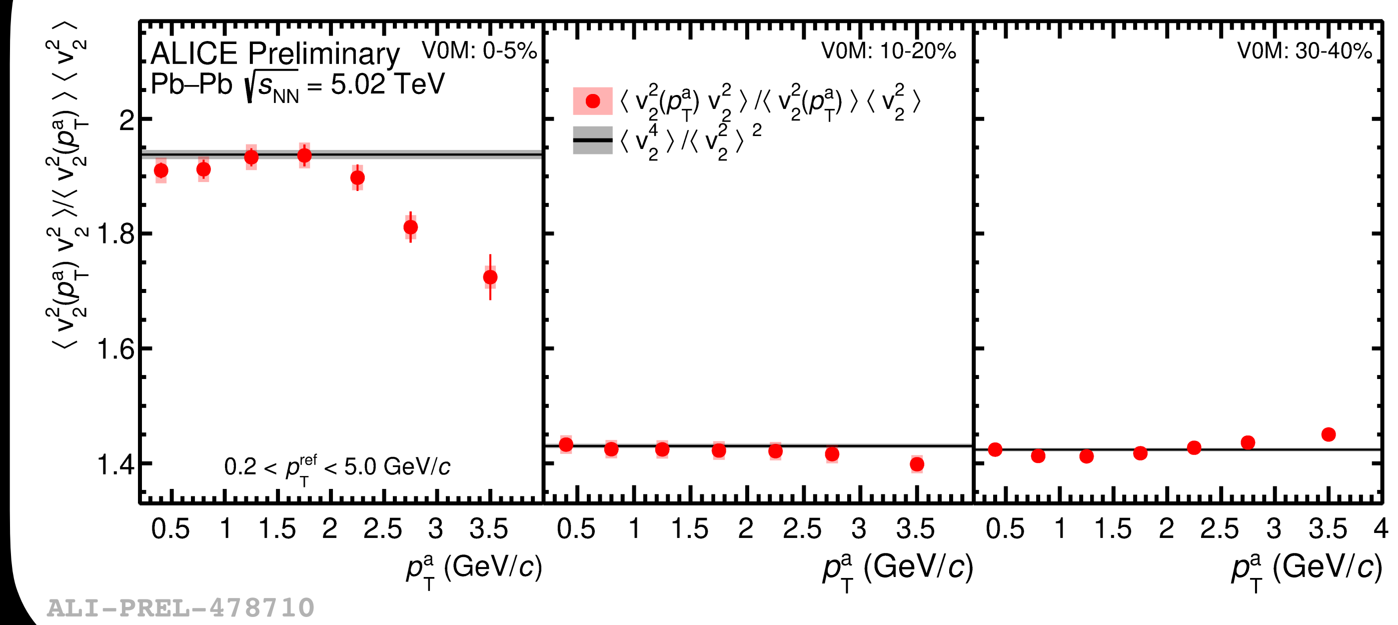
Flow magnitude and angle fluctuations

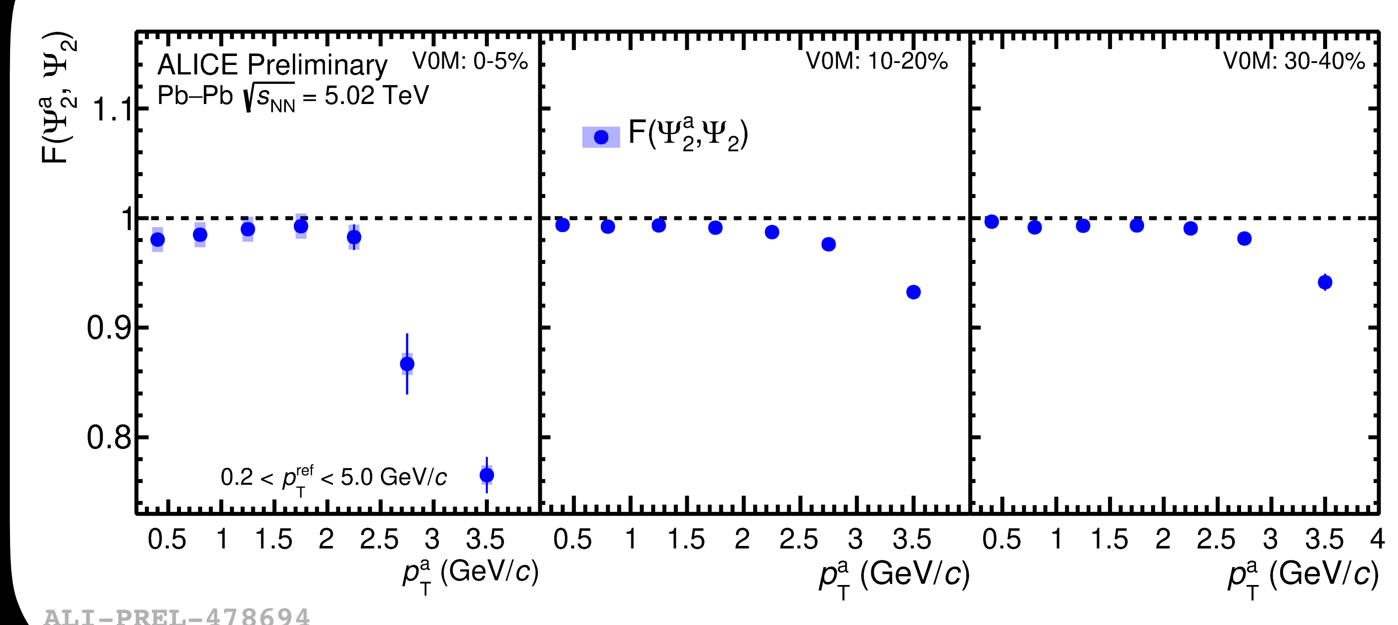
Magnitude:

$$\frac{\langle\langle \cos n(\varphi_1^a + \varphi_2 - \varphi_3^a - \varphi_4)\rangle\rangle}{\langle\langle \cos n(\varphi_1^a - \varphi_3^a)\rangle\rangle\langle\langle \cos n(\varphi_2 - \varphi_4)\rangle\rangle} = \frac{\langle v_n^2(p_T^a) v_n^2\rangle}{\langle v_n^2(p_T^a)\rangle\langle v_n^2\rangle}$$

Angle:

$$F(\Psi_n^a, \Psi_n) = \frac{\langle\langle \cos[n(\varphi_1^a + \varphi_2^a - \varphi_3 - \varphi_4)]\rangle\rangle}{\langle\langle \cos[n(\varphi_1^a + \varphi_2 - \varphi_3^a - \varphi_4)]\rangle\rangle} \approx \langle \cos 2n[\Psi_n(p_T^a) - \Psi_n]\rangle$$

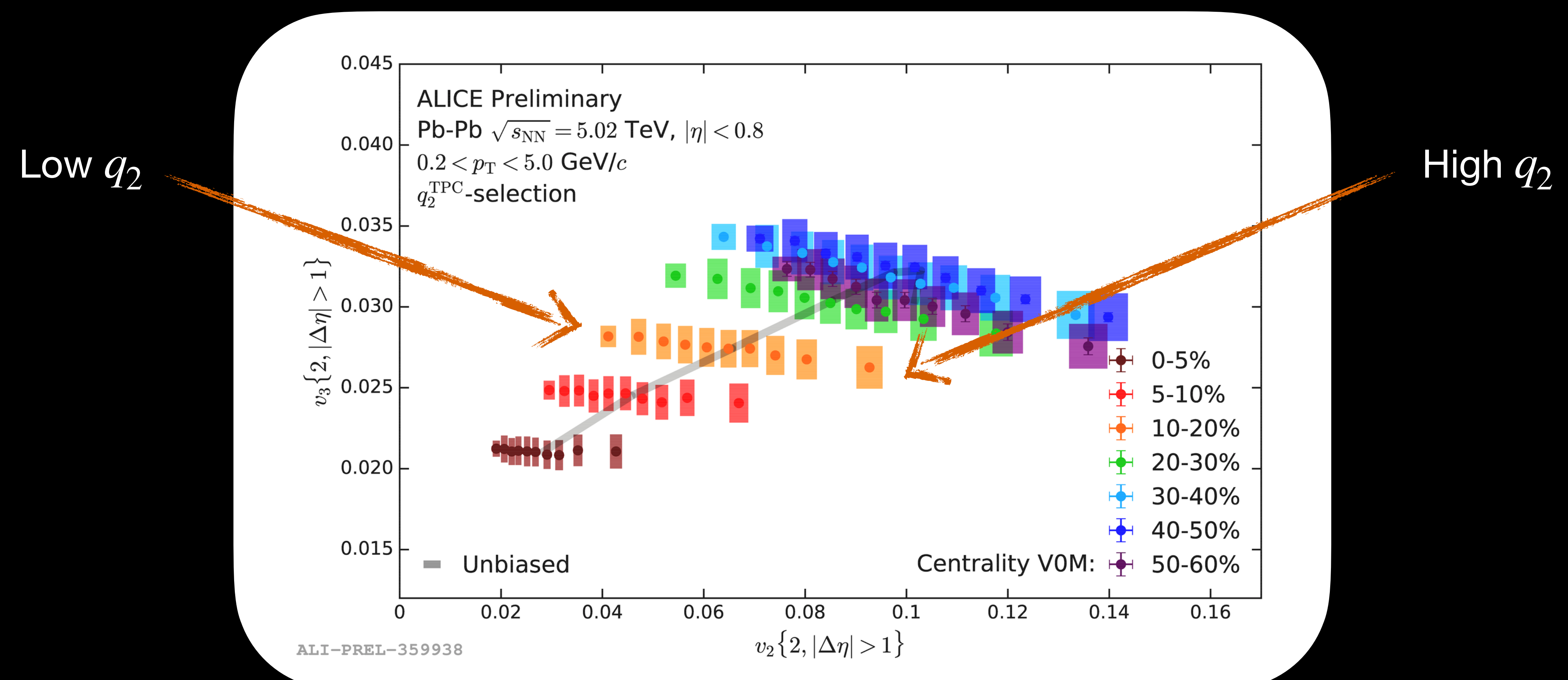




- Both flow magnitude and angle fluctuations are p_T dependent (deviation from $\langle v_n^4\rangle/\langle v_n^2\rangle^2$ and unity, respectively)
- Deviation most significant in the most central collisions ($\sim 5\sigma$ for magnitude and $> 5\sigma$ for angle fluctuations) ⇨ **discovery**

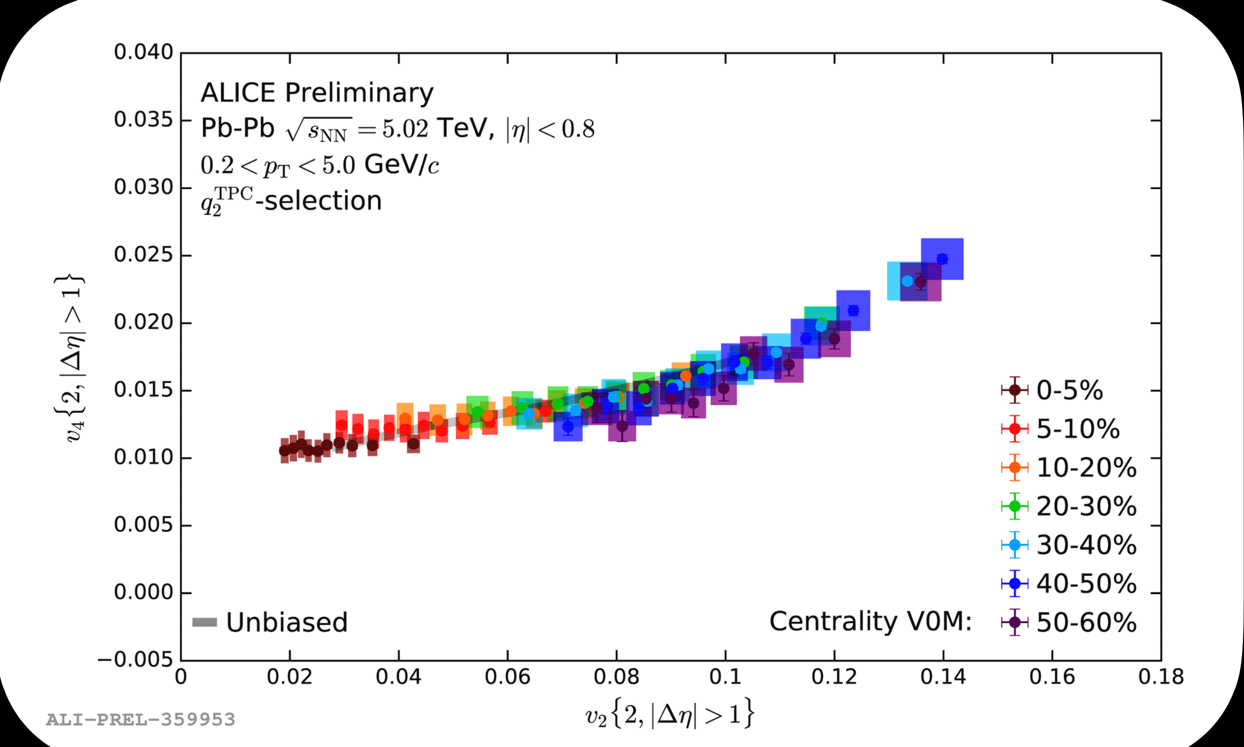
Correlations between harmonics with ESE

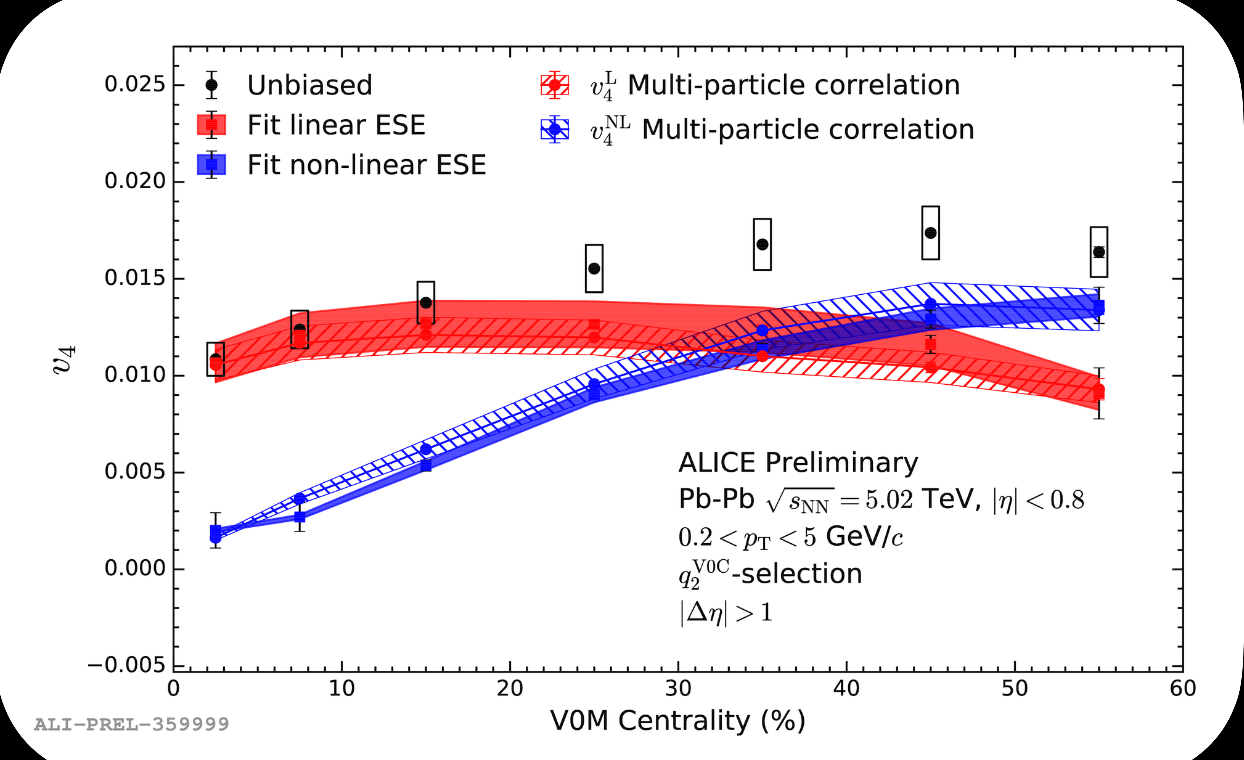
- Event-shape engineering (ESE) selects specific initial eccentricity
- q_2 selection by constructing reduced flow vector
- Negative correlations between v_2 and v_3



Linear and non-linear flow modes

- Positive correlations between v_2 and v_4
- Extracting linear and non-linear responses by fitting v_4 with $v_4 = \sqrt{c_0^2 + (c_1 v_2^2)^2}$ (in each centrality class)
- Non-linear part (ϵ_2 contribution) shows strong centrality dependence while linear part (ϵ_4 contribution) stays almost constant with increasing centrality





Summary

- Flow coefficients $v_n\{m\}$ of different harmonics and different orders of multi-particle correlations were measured in heavy-ion collisions with ALICE
- Probability density function of v_2 was measured using multi-particle cumulants and has non-trivial transverse momentum dependence
- New observables allow to differ between the contributions from flow magnitude and flow angle fluctuations to the flow vector fluctuations
- Using event-shape engineering, it is possible to select subsets of events with different shapes of *p.d.f.*, obtain important information on correlations between different flow harmonics, and also extract linear and non-linear flow modes

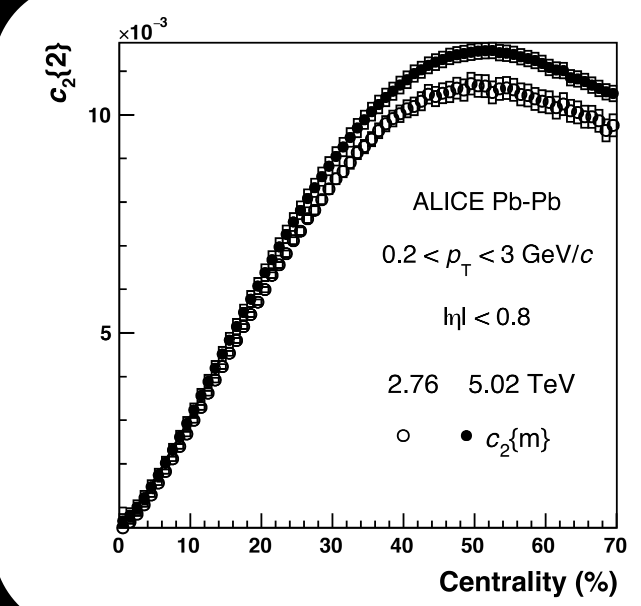
Thank you for you attention!

BACK UP

Multi-particle correlations

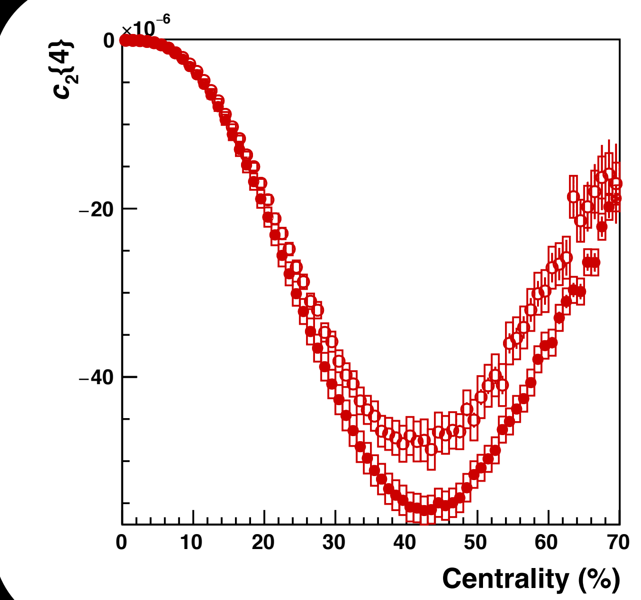
- Two particles with φ_1, η_1 and φ_2, η_2
- Two-particle **correlation**: $\langle\langle 2 \rangle\rangle = \langle\langle \cos n(\varphi_1 - \varphi_2) \rangle\rangle$
- Four-particle **correlation**:
  $\langle\langle 4 \rangle\rangle = \langle\langle \cos n(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4) \rangle\rangle$

ALICE, JHEP 1807 (2018) 103



- Two-particle **cumulant**: $c_n\{2\} = \langle\langle 2 \rangle\rangle$
- Four-particle **cumulant**: $c_n\{4\} = \langle\langle 4 \rangle\rangle - 2\,\langle\langle 2 \rangle\rangle^2$
  - $\langle\langle 4 \rangle\rangle$ contains (lower order) correlations between $\varphi_1 - \varphi_3$, $\varphi_2 - \varphi_4$ and $\varphi_1 - \varphi_4$, $\varphi_2 - \varphi_3$ that have to be subtracted

ALICE, JHEP 1807 (2018) 103



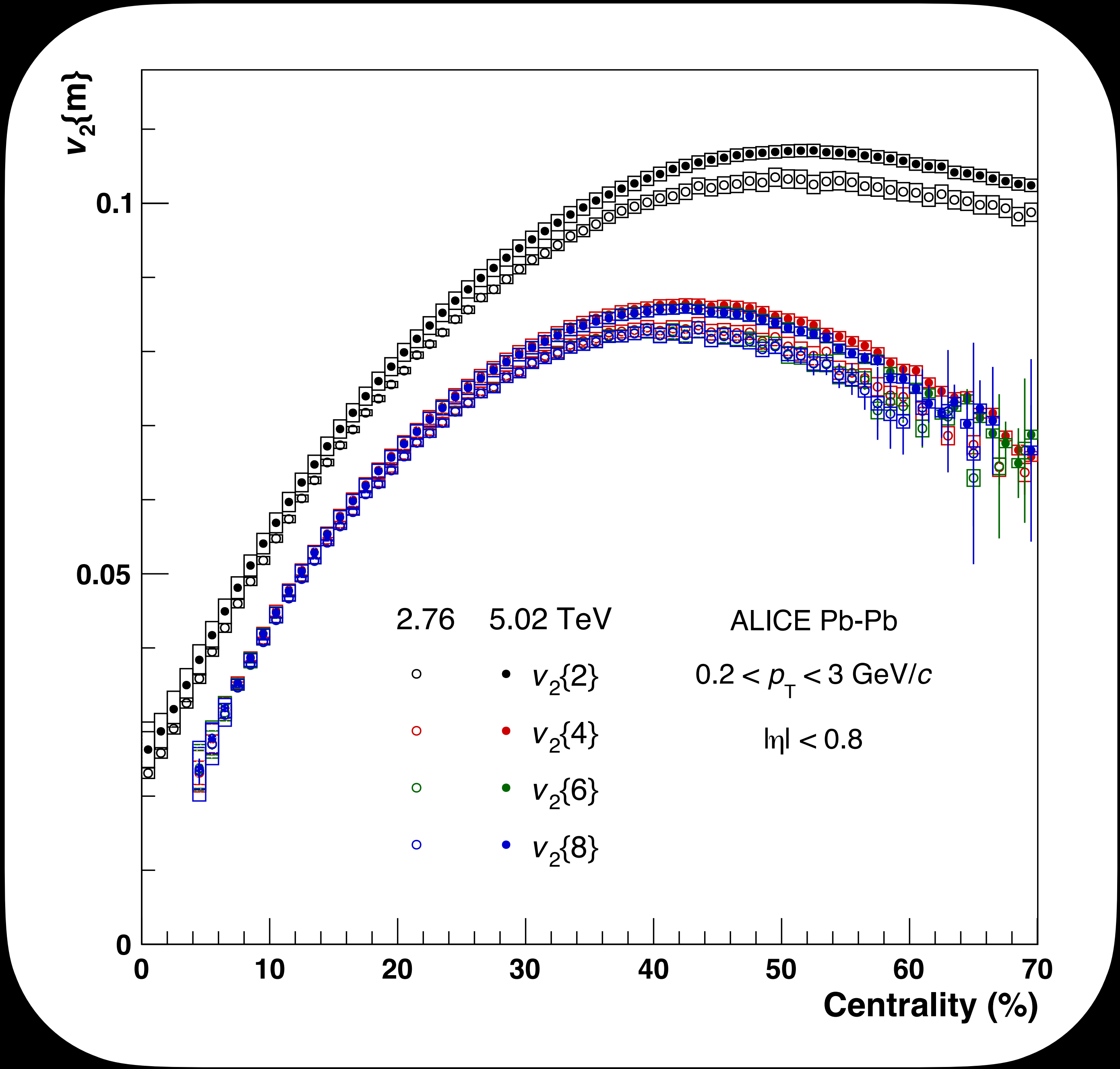
Multi-particle cumulants

- $c_n\{2\} = \langle\langle 2 \rangle\rangle_{n,-n}$
- $c_n\{4\} = \langle\langle 4 \rangle\rangle_{n,n,-n,-n} - 2\langle\langle 2 \rangle\rangle^2_{n,-n}$
- $c_n\{6\} = \langle\langle 6 \rangle\rangle_{n,n,n,-n,-n,-n} - 9\langle\langle 4 \rangle\rangle_{n,n,-n,-n}\langle\langle 2 \rangle\rangle_{n,-n} + 12\langle\langle 2 \rangle\rangle^3_{n,-n}$
- $c_n\{8\} = \langle\langle 8 \rangle\rangle_{n,n,n,n,-n,-n,-n,-n} - 16\langle\langle 6 \rangle\rangle_{n,n,n,-n,-n,-n}\langle\langle 2 \rangle\rangle_{n,-n}$
  $-18\langle\langle 4 \rangle\rangle^2_{n,n,-n,-n} + 144\langle\langle 4 \rangle\rangle_{n,n,-n,-n}\langle\langle 2 \rangle\rangle^2_{n,-n} - 144\langle\langle 2 \rangle\rangle^4_{n,-n}$

Multi-particle cumulants

- **Flow coefficients:**
  - $v_n\{2\} = \sqrt{c_n\{2\}}$
  - $v_n\{4\} = \sqrt[4]{-c_n\{4\}}$
  - $v_n\{6\} = \sqrt[6]{\frac{1}{4}c_n\{6\}}$
  - $v_n\{8\} = \sqrt[8]{-\frac{1}{33}c_n\{8\}}$
- Difference (at the same energy) caused by **non-flow** and **fluctuations**
- Non-flow: flow-like correlations caused by jets and decays of resonances

ALICE, JHEP 1807 (2018) 103



Linear and non-linear flow modes

- No correlations between linear and non-linear components
- Linear part of v_4 stays unchanged with changing the event shape
- Significant increase of non-linear part of v_4 when modifying the event shape